Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 69 (2015) 2031 – 2038
Energy Procedia

International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014

Annual performance calculations for CSP plants under different feed-in tariff schemes

J. Dersch*, S. Dieckmann, K. Hennecke

German Aerospace Center (DLR), Institute of Solar Research, 51170 Köln, Germany

Abstract

Different tariffs for solar electricity for certain periods of the day require special operating strategies for the CSP plants. This paper shows an example for using such operating strategies in a software tool for annual performance calculations. The example is made according to the Spanish CSP market, where the boundary conditions have been changed dramatically for the existing CSP plants.

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG

Keywords: model, annual yield calculation; operating strategy

1. Introduction

In Spain about 50 CSP plants have been build and commissioned since 2007. These plants were planned and erected under a special feed-in-tariff scheme and their design and profitability calculations were based on that tariff scheme. Recently, the Spanish government changed the tariff scheme radically. Though not all details are fixed yet, this will force the operating companies to adapt their strategy in order to limit the financial harm.

This paper shows the capabilities of the software tool Greenius [1][2] to consider such changes and to use operating strategies (OS) to simulate the electrical output as well as the economic impact of such measures. One important advantage of CSP plants with thermal storage, in comparison to other renewable energy plants like PV and

*Corresponding author. Tel.: +49-2203-6012219; fax: +49-2203-6014141.
E-mail address: juergen.dersch@dlr.de

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.03.214

wind, is their capability to produce dispatchable electricity even after sunset. This feature might be very important for higher fractions of fluctuating renewable energies in a regional grid [3]. Additionally, the storage capacity provides the margin to fit the OS to the feed-in-tariff scheme.

2. The software tool Greenius

The software tool Greenius has been developed at DLR since several years. It is designed to facilitate fast and simple performance calculations of concentrating solar power (CSP) and other renewable energy systems based on hourly plant performance simulations for a typical year [1]. The initial focus was on renewable electricity generation with emphasis on concentrating solar power generated by parabolic trough plants. Greenius is continuously extended e.g. to simulate also solar towers, solar process heat generation and solar cooling. It offers a combination of fast technical performance calculations, economical calculations and user interfaces for parameter manipulation and analysis of the results. Third party meteorological data and performance maps generated with other software tools can easily be integrated.

Recently, the option of considering user-defined operating strategies has been added as well as simulation with higher temporal resolution than one hour. The utilization and the impact of different OS is described in this paper. The software Greenius is distributed free of charge and can be downloaded from [2]. From this link more information about the software as well as a manual are available.

3. Scenario

Most plants in Spain were planned and designed under the assumption that a flat feed-in-tariff (FiT) will be available for 25 years. Operators could choose a full flat tariff (option A) or a lower flat base tariff plus the spot market price which they could achieve (option B). In addition there was no time restriction for the delivery of electricity. Furthermore utilization of a certain amount of natural gas to compensate storage losses (12 or 15%, depending on the tariff option) was allowed.

Currently these FiT have been withdrawn and new regulations are under discussion. One possible option are different electricity prices depending on the hour of day and/or the seasonal variations. For the operating companies this means that they have to modify their operating strategies in order to produce as much electricity as possible during high tariff hours. This is of particular importance for those plants having a thermal storage with several hours capacity. For the study presented here a hypothetical but not unrealistic tariff scheme has been used. It is shown in Fig. 1 and is based on 278 €/MWh for peak hours, 100 €/MWh for normal hours and no payment for night time hours. Fig. 1 shows a comparison of both tariffs.

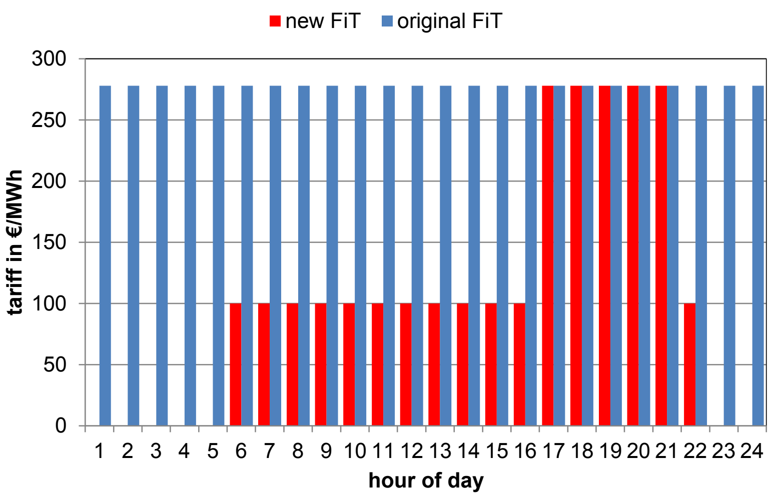

Fig. 1. FiT according to the time of day

4. Implementation of user-defined operating strategies in the simulation software

Although the formulation of an OS in words or in a higher programming language is quite simple, it is more complicated in the case where a user shall define the OS just by setting input parameters but nevertheless shall have the flexibility to define different strategies. This complexity originates from the many different OS that must be implemented in the software since the user has no access to the source code. The input parameters are typically limits and priorities. The reimbursement for electricity often depends on the time-of-day and may also vary seasonally. The software tool should be able to consider these variations.

In CSP plants with thermal storage (TES) the operators have some degrees of freedom for the plant operation:

- Send the available heat to the power block or to the TES
- Run the power block at full load or at reduced load
- Use heat from the TES to operate the power block even during periods with no heat from the solar field
- Use additional heat from fossil fired auxiliary heaters (if the plant has such devices) to run the power block

Typically a reasonable OS for CSP plants is the so called “solar-only-operation”, which can be defined as:

- Operate the solar field at maximum possible heat production
- Use the heat from the solar field to operate the power block at maximum possible load
- When the heat delivered by the solar field exceeds the maximum power block input, use this surplus heat to charge the TES
- If the TES is totally charged, defocus parts of the solar field until the heat output matches the maximum power block input
- If the heat delivered by the solar field decreases in late afternoon, discharge the TES to run the power block at maximum possible load and continue discharging of TES in the evening until the storage is empty.

This “solar-only” OS might be considered as “natural” OS for CSP plants. Therefore it is hardcoded in Greenius and will be used as default OS as long as the user does not define another one. Defining an OS in Greenius can be done by defining up to nine different strategies (groups of limits and priorities) and assign a certain strategy to each time period to be simulated. Fig. 2 shows a screenshot of the Greenius OS input form. The upper table shows the allocation of strategy 1 to 4 to individual time periods of the year. In this example an hourly calculation was done, thus we have 365×24 individual time periods for the whole year. In the lower table of Fig. 2 several thresholds, limits and priorities can be set for each single strategy. The meanings of these parameters are:

Columns 2 – 4 in the lower table of Fig. 2 are used to define whether and to which extend the storage can be discharged.

Storage discharge threshold (Discharge THR)

This value delivers the threshold for the following two storage dispatch fractions. It refers to the maximal thermal input the power block can accept under nominal conditions. (Discharge THR = 0.5 means: the threshold is 50% of the power blocks nominal heat input.)

Depending on the heat actually delivered by the solar field in the current time instance, the additional heat taken from the storage may be limited to different fractions defined by the columns 3 and 4. Therefore the parameters given in columns 2-4 are used in conjunction.

Storage discharge fraction for high solar field outputs (Discharge > THR)

This factor refers to the maximal storage discharge power. If the actual heat from the solar field is greater than "Discharge > THR", the maximal storage discharge is limited by this fraction. This parameter might be used for example to utilize heat from the storage to run the power block at full load when the solar field delivers high outputs.

Storage discharge fraction for low solar field outputs (Discharge < THR)

This fraction refers to the maximal storage discharge power. If the actual heat from the solar field is smaller or equal to "Discharge < THR", the maximal storage discharge is limited by this fraction. This parameter can be used for example to limit the storage discharge during nighttime in summer to allow 24h operation of the power block.

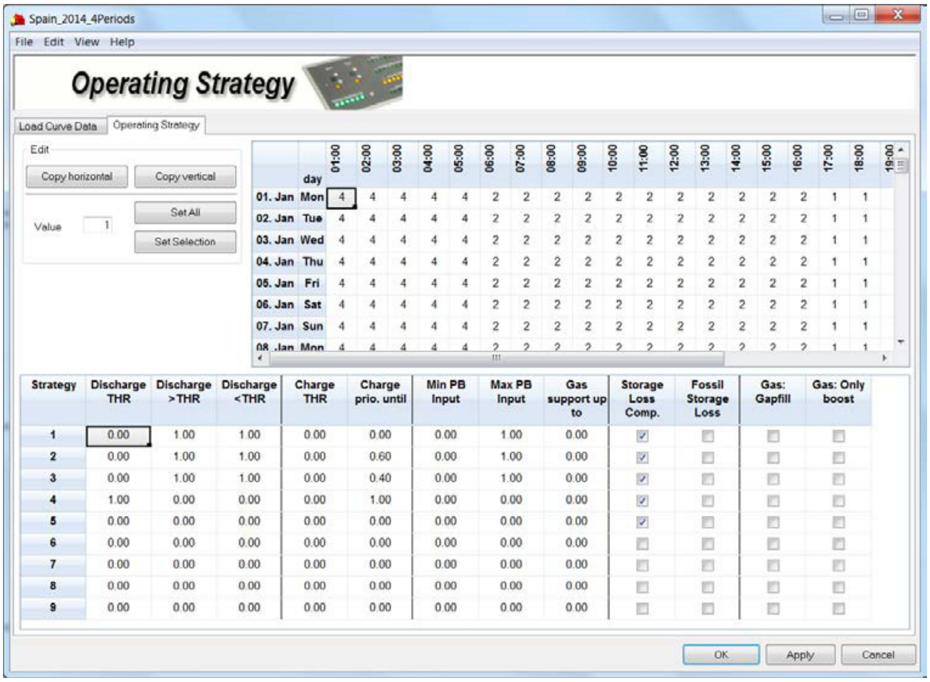

Fig. 2. Screenshot of the Greenius form for defining OS

Columns 5 and 6 are used to define the storage charging

Storage buffer threshold (Charge THR)

This fraction refers to the maximal power block input. If the heat from the field is higher than this threshold, the storage is filled up to the "Storage buffer level" (Charge prio. until). When it is set to 0, the storage buffer level is applied always. When it is set to 1 the storage buffer level priority is disabled.

Storage buffer level (Charge prio. until)

This fraction refers to the net capacity of the storage. It defines the level up to which the storage is filled up with first priority. By using this parameter the storage can be filled to a certain level before the power block starts. Fluctuations of solar heat delivered by the solar field can be balanced in a better way and the number of turbine starts may be reduced by defining a certain storage buffer level. Furthermore this parameter can be used to shift power production to the hours after sunset, like in this paper.

Minimum power block input (Min PB Input)

This fraction refers to the maximal power block input. It describes the minimum heat input at which the power block starts during the relevant period. If this parameter is set to 1 the power block starts only when the available heat (from SF, storage and auxiliary heater) is sufficient to run the power block at full load.

Maximum power block input (Max PB Input)

This fraction refers to the maximal power block input. It limits the power block heat input during the period. Setting this parameter to values below 1 restricts the power block to a level below the maximum load and extends the number of operating hours from the storage.

Storage Loss Compensation

The 2-tank molten salt storage has constant losses independent of the load status. The compensation of these losses has the highest priority if this box is checked. In this case the storage is filled up to its minimum (defined in the storage input window) with solar thermal energy even though the solar thermal energy does not exceed the thermal energy demand of the power block.

The columns “Gas support up to”, “Fossil Storage Loss Compensation”, “Gas: Gapfill”, and “Gas: Only boost” are not used in this paper, their meaning might be checked in the Greenius manual.

The four periods in Fig. 2 are defined for a remuneration scheme which is based on 278 €/MWh for peak hours (16:00-21:00), 100 €/MWh for normal hours (5:00-16:00, 21:00-22:00) and no payment for night time hours (22:00-5:00). At a first sight this would imply 3 different periods: peak hours, normal hours and night hours, but with these 3 periods it is not possible to conceive an OS leading to a maximum electricity generation during peak hours. This requires that the storage level is sufficiently high at the beginning of the peak period since this period is partly after sunset. Strategy #1 in the lower table of Fig. 2 is for the peak hours and strategy #4 is for night hours. Strategies #2 and #3 are both for “normal hours” but #2 is applied from September 22nd until March 20th and #3 from March 21st until September 21st. The only difference between #2 and #3 is the storage charge priority level. During summer, this level is 0.4 and during winter it is 0.6. This means that the TES is charged with the highest priority until the defined storage level is reached and the power block has only the second priority during these periods. When the TES reaches the given level, the power block gets the highest priority and further charging of TES is only done when the solar field delivers excess heat over the maximum power block input.

Defining 2 different periods for the “normal” operation hours is based on the consideration that the irradiation on the aperture during peak tariff hours depends on the sunset and thus the season. Consequently, the storage content at the beginning of the peak period should be higher in winter season. Comparison with cases using 1 or 3 periods for “normal” operation hours have shown that with 2 periods the highest electricity production rate during peak hours can be reached. The values of 0.4 and 0.6 for storage buffer levels were found by a trial-and-error procedure.

The major technical and economic assumptions used for this comparison are summarized in table 1.

Table 1. Major technical and economic assumptions

Parameter	Unit	Value
Nominal gross electric output	MW	50
Thermal storage capacity	MWh	940
Solar field aperture area	m²	510120
Collector type	-	Eurotrough
Absorber type	-	Schott PTR70
Site	-	Guadix, Spain
Annual sum of DNI	kWh/m²	2111
Total investment costs	Mio. €	280
Annual insurance costs	%	1
Annual O&M costs	Mio. €	5.9
Debt/equity ratio	-	70/30
Interest rate	%	5.6
Debt term	years	12
Plant life time	years	25
Construction period	years	2
Depreciation period	years	15
Depreciation method	-	linear

5. Annual results for different FiT

Table 2 shows results of three simulation runs with different OS according to different remuneration schemes. The first case is according to the original flat FiT with 12% fossil fuel utilization on an annual basis. The second one is for the same case without fossil fuel utilization and the third case is for the new FiT with 4 periods as described above.

Disabling the fossil fuel option will reduce the capacity factor by about 4 %-points while the new FiT scheme will reduce it by 6%-points. The levelized cost of electricity (LCOE) will increase under the new FiT but more meaningful for the owners is the reduction in internal rate of return (IRR). The original IRR was 13% (under the technical and economic assumptions used in this example) but will go down to 2.2%. The former value might be considered as sufficient for investors while the latter one would normally not stimulate investment in such a project. Without adapting the OS the plant will produce almost 21000 MWh during nighttime and thus without payment.

The results show that Greenius can be used to simulate different scenarios for the FiT and different operating strategies. It does not contain an optimization tool yet, therefore the user has to do this “manually”. The situation in Spain is unique since the boundary conditions were changed when the plants were already in operation, but generally varying FiT and feed-in restrictions may exist in other countries too. In the example given above, the operating strategies applied are based on charging the storage to a certain minimum level with the highest priority with different levels during summer and winter half year. As a result net electricity production during peak hours is increased by 36% compared to the case under the original FiT and no fossil fuel utilization.

Table 2. Results from 3 simulation runs with different OS

Project case	Unit	Original FiT 12% fossil fuel	Original FiT no fossil fuel	New FiT no fossil fuel
Solar net electricity production	MWh	146409	146409	137581
Total net electricity production	MWh	167741	146409	137581
Capacity factor	-	0.421	0.379	0.357
Annual solar share (net)	%	88.0	100	100
Total heat production of SF	MW_th	473143	473143	473143
Annual dumping fraction	%	6.7%	6.7%	11.7%
No. of hours with empty storage	-	4400	4400	2822
No. of hours with full storage	-	248	248	473
Net electricity during peak hours	MWh	48130	42354	57452
LCOE	€/kWh	0.187	0.190	0.202
IRR	%	13.0	11.7	2.2

It should be kept in mind that using a predefined OS does not mean the same as optimizing the day-by-day operation with consideration of weather forecasts. The latter procedure will be done by plant operators in different forms. They will at least consider the normal weather forecast from radio or TV or in a more sophisticated scheme; they will use a computer system proposing a certain strategy with frequently updated DNI forecasts.

6. Comparison of results for individual days

Fig. 3 shows a comparison of 3 individual days for the original FiT and the new FiT scheme, both without fossil fuel utilization. It is obvious that the OS for the new FiT does not produce any electricity during the night hours since there will be no payment. Furthermore, the importance of priority hours can be seen, most significant for the November day, where the electricity production is completely shifted towards the priority hours. This is a day with fairly good DNI in the morning and reduced DNI after noon. The July day is almost perfect concerning the DNI curve and it can be seen that there is some storage content available in the morning from the preceding day. During the 11th hour of that day, heat from solar field was not used to produce electricity but rather to charge the storage to the required level. A similar behavior is shown for 12th March. Here again, during the first hour with heat production of the solar field, the storage priority prevails and no electricity is produced.

Reduction of heat flow to power block and reduced electricity production during periods without solar field heat is caused by the lower maximal output when the power block is operated from storage. For discharging the heat flow from storage is limited due to mass flow restrictions and double heat exchange from heat transfer fluid to molten salt and back.

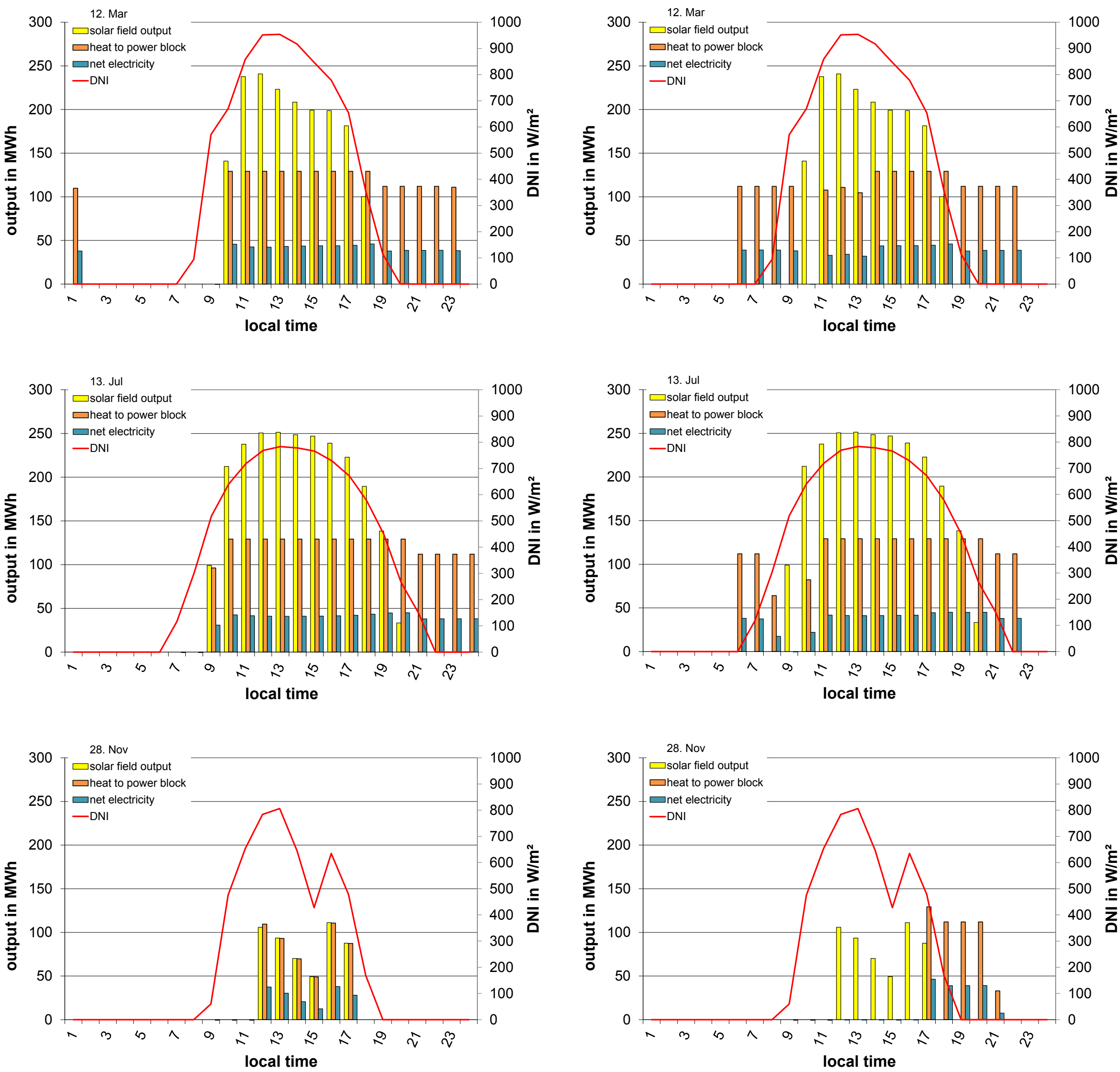

Fig. 3. Results for 3 days for the original FiT (left) and the new FiT (right)

7. Conclusions

User defined OS are important for annual yield simulation tools for markets where different tariffs for several time periods are defined. This paper shows an example for the software tool Greenius where an OS was defined to increase electricity production during peak hours and thus to increase the revenues.

The total annual electricity production typically decreases by using such an OS but this is no longer the relevant figure of merit since there are periods without payment. More meaningful in this context are total electricity production during peak hours or IRR as financial index. The IRR for the plant under the original flat FiT with 12% allowed fossil fuel utilization was 13% (under the technical and economic assumptions used in this example). It decreases to 11.8% when the fossil fuel utilization is not allowed and further down to 2.2% with a FiT scenario based on 278 €/MWh for peak hours (16:00-21:00), 100 €/MWh for normal hours (5:00-16:00, 21:00-22:00) and no payment for night time hours (22:00-5:00).

Acknowledgements

The work presented here as well as publishing and further development of Greenius is enabled through funding by the German Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag (Funding reference number: 0325427)

References

[1] Dersch J, Hennecke K, Quaschning V, Free Greenius – New Options and Availability, SolarPACES 2012 Conference, 11.-14. September 2012, Marrakech, Morocco
[2] http://freegreenius@dlr.de
[3] Jorgenson J, Denholm P, Mehos M, Estimating the Value of Utility-Scale Solar Technologies in California under a 40% Renewable Portfolio Standard, Technical Report NREL/TP-6A20-61685, May 2014